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## HIGH-VELOCITY WHITE DWARFS: THICK DISK, NOT DARK MATTER

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### ABSTRACT

We present an alternative interpretation of the nature of the extremely cool, high-velocity white dwarfs identified by Oppenheimer *et al.* (2001) in a high-latitude astrometric survey. We argue that the velocities of the majority of the sample are more consistent with the high-velocity tail of a rotating population, probably the thick disk, rather than a pressure-supported halo system. Indeed, the observed numbers are well matched by predictions based on the kinematics of a complete sample of nearby M dwarfs. Analysing only stars showing retrograde motion gives a local density close to that expected for white dwarfs in the stellar ( $R^{-3.5}$ ) halo. Under our interpretation, none of the white dwarfs need be assigned to the dark-matter, heavy halo. However, luminosity functions derived from observations of these stars can set important constraints on the age of the oldest stars in the Galactic Disk.

*Subject headings:* stars: white dwarfs; Galaxy: stellar content, dark matter

### 1. INTRODUCTION

Tracking down the nature of dark matter could be described as the astronomical obsession of the twentieth century. The concept emerged through Oort's comparison of the census of luminous material (stars, gas, dust) in the Solar Neighbourhood with dynamical estimates of the local mass density derived from the motions of K giants, high in the Galactic Disk (Oort, 1932). Like Zwicky's (1933) near-contemporary suggestion that cluster-galaxy kinematics required dark mass on much larger scales, the problem of the local 'missing mass' was not taken up immediately. However, the discrepancy in mass densities, a factor of  $\sim 3$ , prompted a flurry of survey activity in the 1960s and 70s, largely centred on what proved to be substantial overestimates of the number density of M dwarfs (see Reid & Hawley, 2000, ch. 7). Debate continues over the significance of the Oort limit discrepancy (Bahcall *et al.*, 1992; Cr     *et al.*, 1998).

In a cosmological context, dark matter came to prominence with the realisation that rotation curves of many galaxies were not Keplerian at radii beyond the visible extent of the disk (e.g. Rubin, Ford & Thonnard, 1978). Some were flat, implying that the enclosed mass increases linearly with radius (Ostriker, Peebles & Yahil, 1974). Extrapolating to the Holmberg radius, the total mass approaches  $\sim 10^{12} M_{\odot}$ , with mass-to-light ratios more than an order of magnitude higher than expected for an old stellar population. Ostriker *et al.* suggested that the additional material could be distributed in a near-spherical structure (a 'heavy halo'), thereby dynamically stabilising the disk in spiral galaxies (Ostriker & Peebles, 1973). The implied radial density law is  $\rho_{HH}(R) \propto R^{-2}$ , where  $R$  is the distance from the centre of the Galaxy. This is substantially flatter than the  $\rho_S(R) \propto R^{-3.5}$  density distribution of the  $\sim 3 \times 10^9 M_{\odot}$  traditional (Population II) stellar halo (Schmidt, 1975).

Subsequent developments in the field have been re-

viewed by Trimble (1987), Fich & Tremaine (1991) and Ashman (1992). The most recent estimates, based on satellite galaxy motions, place the mass of the Milky Way at  $\sim 5 \times 10^{11} M_{\odot}$  for  $R < 50$  kpc. (Wilkinson & Evans, 1999). Approximately 10% of this mass can be accounted for by stars, gas and dust in the Galactic disk and the stellar halo (Alcock *et al.*, 2000). Dark matter candidates for the remaining 90% include exotic particles, cold molecular gas, and compact objects, ranging from  $10^6 M_{\odot}$  black holes through brown dwarfs to space rocks. Of these categories, the last is potentially most accessible to direct astronomical observation through gravitational microlensing (Paczynski, 1986). A number of extended photometric monitoring campaigns have been conducted, directed towards the high star-density regions of the LMC, SMC and the Galactic Bulge, and a substantial number of lensing events detected.

The contribution made by MACHOS to the dark halo is still uncertain. From their most recent analysis of data taken in the central regions of the LMC, the MACHO group have detected 17-19 events, from which they estimate the contribution of MACHOs to dark matter to be about 20%,  $\sim 9 \times 10^{10} M_{\odot}$  (Alcock *et al.* 2000). On the other hand, data from the EROS group cover a wider region of the LMC, within which they have detected at most 2 events. Based on those detections, they estimate that MACHOS contribute between 0 and 20% of the heavy halo (Lassere *et al.* 2000). While the exact locations of the lenses remain controversial, mainly because the simple microlensing light curve is inadequate to provide information on the lens locations, there are two binary events – MACHO 98-SMC-1 and MACHO LMC-9 – for which the lens locations have been determined with reasonable certainty (Albrow *et al.* 1999, Alcock *et al.* 1997, 1999). In both these cases, the caustic crossing timescales suggest that the lenses are most likely in the Magellanic Clouds, and this has been used to argue that most of the lenses may

be Magellanic Cloud members (e.g. Graff, 2000; Sahu and Sahu, 1998). Furthermore, the very different time scales of the events observed towards the LMC and the SMC seem to be inconsistent with MACHOs located in the halo (Sahu, 1994; 2001).

Whether MACHOs are Galactic or members of the Magellanic Clouds, it is clear that they are a minority constituent of the heavy halo. Moreover, the best estimate of the mass of the foreground lensing objects, based on the distribution of event timescales and the assumed kinematics, proves to be surprisingly high,  $\langle M \rangle = 0.5 \pm 0.3 M_{\odot}$ . Indeed, probably the most significant result from the microlensing projects is the stringent limit set on possible dark matter contributions from lower-mass objects such as brown dwarfs.

The set of compact astronomical objects with  $M \sim 0.5 M_{\odot}$ , and luminosities sufficiently low to escape detection, is small; white dwarfs are the obvious candidate, presumably fossil remnants of a primordial stellar population (Population III). Such an hypothesis has significant implications, particularly for star formation theory: the corresponding mass function,  $\Psi(M)$ , must peak strongly at intermediate masses, avoiding over-enrichment of Population II by supernovae, and matching the number of long-lived low-mass dwarfs to the stringent constraints set by general starcounts (Graff & Freese, 1996; Reid *et al.*, 1996). While there is only weak evidence for radical changes in  $\Psi(M)$  in the abundance range spanned by disk and halo, a number of theoretical models have been devised which accommodate those requirements at primordial abundances (Chabrier *et al.*, 1996; Chabrier, 1999). Even those models, however, produce sufficient ejecta that they have difficulty matching the observed abundance ratios of light elements in Population II stars (Gibson & Mould, 1998; Fields *et al.*, 2000).

Accepting these caveats, it is possible to search for the white dwarf members of the purported Population III heavy halo using their unusual colours. Recent theoretical models (Bergeron *et al.*, 1995; Hansen, 1999) predict that old, cool, hydrogen-atmosphere white dwarfs have flux distributions which depart significantly from blackbody curves, due mainly to  $H_2$  absorption (Mould & Liebert, 1978). A small number of examples have been found in the field (e.g. LHS 3250, Harris *et al.*, 1999), although none have the low luminosities ( $M_R \sim 17$ ) expected for 12-14 Gyr-old degenerates. Such objects might have escaped attention in previous large-scale surveys.

Almost contemporaneously with the theoretical work, analysis by Ibata *et al.* (1999) of second-epoch images of the Hubble Deep Field, taken two years after the first-epoch data, led to the tentative identification of two to five very faint, blue, point-like sources which appeared to exhibit measureable proper motion. If those sources were heavy-halo white dwarfs, the mass density would be sufficient to account for all of the heavy-halo dark matter. However, the proper motions have recently been withdrawn based on third epoch HST observations, taken three years after the second-epoch observations (Richer, 2001).

The local mass density of the heavy halo is  $\sim 10^{-2} M_{\odot} \text{ pc}^{-3}$  (for an  $R^{-2}$  mass dependence). If  $0.5 M_{\odot}$  objects contribute 20% of the dark halo, the Solar Neighbourhood density is  $0.004 \text{ MACHOs pc}^{-3}$ . Ibata *et al.*

(2000) identify two nearby cool white dwarfs, which they suggest are potential examples of this type of object. Flynn *et al.* (2001), however, failed to identify any likely counterparts amongst published proper motion surveys, while Monet *et al.* (2000) identified only a single candidate halo white dwarf in a proper motion survey combining accepted and rejected POSS II plate material in 35 fields ( $\sim 1380$  square degrees). Although the latter object is spectral type DC, the spectrophotometric properties are consistent with a cooling-age significantly younger than 12 Gyrs, making it likely to be a member of the stellar halo. Finally, Harris *et al.* (2001) report the detection of an extremely cool white dwarf, SDSSp J133739.40+000142.8, from SDSS commissioning data. However, the system has a low space motion, and is probably a low-mass disk star with a helium core.

Most recently, Oppenheimer *et al.* (2001; O2001) have completed a deep proper-motion survey towards the South Galactic Cap and have identified 38 cool white dwarfs. Based on kinematics, they assign those stars to a halo-like population, and argue that most are members of the heavy halo. If confirmed, this would be a result of considerable significance. However, we argue that the O2001 analysis fails to meet the burden of proof required for such a radical hypothesis. We present an alternative scenario, explaining the observations in terms of conventional stellar populations. In the following section we discuss the Oppenheimer *et al.* observations in the broader context of stellar population kinematics; the final section summarises our conclusions.

## 2. GALACTIC POPULATIONS AND LOCAL KINEMATICS

### 2.1. Heavy-halo white dwarfs?

Oppenheimer *et al.*'s sample is drawn from 196 Schmidt fields, covering 4165 square degrees towards the South Galactic Cap. They derive BRI magnitudes and proper motions for their sample by combining measurements of IIIaJ, IIIaF and IVN plate material from the UK/AAO Schmidt. The (B-R) colours are used to estimate photometric parallaxes from a linear colour-magnitude relation, with uncertainties of  $\sim 20\%$ . Radial velocities have not been measured for any of the white dwarfs; indeed, most have featureless DC-type spectra. However, towards the Galactic Poles, transverse motion depends most strongly on the U and V velocity components, motion towards the Galactic Centre and in the direction of Galactic rotation respectively. Thus, while the available data do not permit a reliable estimate of W, the velocity perpendicular to the Galactic Plane, planar (U, V) velocities can be estimated from the astrometric data.

Oppenheimer *et al.* derive U and V velocities for each target, allowing for Solar Motion (via secular parallax), and setting  $W=0 \text{ kms}^{-1}$  for each star. Systems with

$$\sqrt{U^2 + (V + 35)^2} > 94 \text{ kms}^{-1}$$

fall outwith the limits of a velocity ellipsoid defined by the  $2\sigma$  motions of disk stars (from Chiba & Beers, 2000; CB), and are identified as having halo-like kinematics. Using the  $\Sigma \frac{1}{\sqrt{m_{\text{max}}}}$  method, and limiting the sample to  $R_{59F} < 19.7$ , they derive a density of

$$\rho_{WD}(\text{HH}) = 2.2 \times 10^{-4} \text{ stars pc}^{-3}$$

This is a factor of ten higher than the expected density of white dwarfs in the stellar halo, and Oppenheimer *et al.*

argue that these degenerates are local representatives of dark matter in the Milky Way's heavy halo. We note that the faintest white dwarf is WD0351-564, with  $M_R \sim 15.9$ , almost 1 magnitude brighter than predicted for 12-14 Gyr-old degenerates (Hansen, 1999).

We have computed motions for the O2001 dataset using a slightly different assumption; we adopt the O2001 photometric distance estimate (and associated uncertainty) and proper motion measurements, but set  $V_{rad} = 0 \text{ km s}^{-1}$  rather than setting  $W=0 \text{ km s}^{-1}$ . Since we have no information on either  $W$  or  $V_{rad}$ , both assumptions are equally valid. Moreover, if the O2001 interpretation of these results is correct, it should be sufficiently robust to survive either assumption. We note that the mean  $W$  velocity for the sample under our assumption is  $0.6 \pm 54 \text{ km s}^{-1}$ , giving no indication of our having introduced a significant bias. We also allow for the Solar Motion, adopting  $U_\odot = 10.0 \text{ km s}^{-1}$ ,  $V_\odot = 5.3 \text{ km s}^{-1}$  and  $W_\odot = 7.2 \text{ km s}^{-1}$ , from Dehnen & Binney's (1998) analysis of Hipparcos data.

Figure 1 plots the resulting  $(U, V)$  distribution, where we also show CB-disk  $1\sigma$  and  $2\sigma$  ellipsoids used by O2001, and those appropriate to a non-rotating halo population with dispersion  $120 \text{ km s}^{-1}$ . The most striking feature, in both Figure 1 and Oppenheimer *et al.*'s Figure 3, is the concentration of stars near the boundaries of the CB-disk  $2\sigma$  ellipsoid. Moreover, there is a significant excess of prograde rotators, 34 of 38 stars in our Figure 1, 30 of 38 in Figure 3 of O2001. This is exactly the behaviour expected if a sizeable fraction of the stars are drawn from the high-velocity tail of a rotating population, rather than a non-rotating, pressure-supported halo.

Oppenheimer *et al.* argue that the observed distribution is skewed by difficulties in detecting white dwarfs with high proper motions. In particular, they note that the probability of detecting stars with  $\mu > 3 \text{ arcsec yr}^{-1}$  is less than 10%. Such objects, however, should make only a limited contribution to this survey, since with an average distance of 73 parsecs,  $\mu = 3 \text{ arcsec yr}^{-1}$  corresponds to a transverse motion of  $1040 \text{ km s}^{-1}$ . This is a factor of two higher than the highest velocity plotted in Figure 1, and, indeed, exceeds the local escape velocity.

We can assess completeness at lower motions by plotting the cumulative distribution of proper motions. In a proper-motion limited régime, one expects the number of stars  $N(\mu > \mu_{lim})$  to vary with  $\mu^{-3}$ . Figure 2 shows that the O2001 halo candidates are broadly consistent with that distribution. Stars at 73 parsecs with mildly retrograde orbits ( $V_{tan}$  between 200 and  $350 \text{ km s}^{-1}$ ) have  $0.57 < \mu < 1.01$ . Thus, it seems unlikely that significant numbers of missing high- $\mu$  stars could account for the scarcity of white dwarfs with retrograde motion.

## 2.2. The velocity distribution of nearby M dwarfs

Is there an alternative explanation of the nature of these stars? As noted above, the concentration at high rotational velocities clearly suggests an origin in the disk. Indeed, Oppenheimer *et al.*'s choice of  $2\sigma$  velocity ellipsoids to differentiate disk and halo should lead to significant contamination -  $2\sigma$  selection applied to two uncorrelated parameters excludes only 86% of a sample. In fact, disk con-

tamination does not reach that level since Chiba & Beers' kinematics are derived from a sample of metal-poor disk dwarfs ( $\langle [Fe/H] \rangle \approx -0.6$ ), and are therefore characteristic of an older, higher velocity-dispersion sub-population. Assessing the likely proportion of high-velocity disk white dwarfs demands kinematics for a volume-limited sample of disk stars; local M dwarfs can supply that demand.

Reid, Hawley & Gizis (1995; RHG) have used spectroscopy and astrometry of almost 2000 M dwarfs to construct a volume-limited sample of 514 M-dwarf systems with  $8 < M_V < 15$ . All of those stars have space motions determined to an accuracy of  $10\text{-}20 \text{ km s}^{-1}$  in each co-ordinate, allowing analysis of the kinematics of the local disk. Comparisons with spectroscopic surveys suggest that the data are 95% complete, with the missing stars predominantly at low velocities<sup>1</sup>. We can use these data to derive an estimate of the parameter  $f_{HVD}$ , the fraction of stars in an unbiased sample of the Galactic disk which have velocities exceeding the CD-disk  $2\sigma$  ellipsoid.

The overall velocity distributions are matched poorly by the single Gaussian velocity dispersions implicit in the Schwarzschild ellipsoid model, particularly the rotational component,  $V$ , where there is evidence for multiple components (RHG, Figure 11). The distributions in  $U$  and  $W$  are simpler; the main body of data can be represented as the sum of two distinct Gaussian components, with dispersions of  $\sigma_U = [35, 52]$  and  $\sigma_W = [20, 32] \text{ km s}^{-1}$  respectively. Even in this model, there are indications of departures from Gaussian distributions at high velocities - the régime sampled by O2001. RHG suggested that 15-20% of local stars might reside in the higher velocity-dispersion component, but more detailed analysis shows that the latter stars comprise no more than 12% of the total. Allowing for incompleteness at low velocities, the likely ratio of low- $\sigma$ :high- $\sigma$  stars is  $\approx 90 : 10$ . Thus, the high-velocity component has a local density comparable to that inferred for the 'thick disk' in recent star-count analyses (Ohja *et al.*, 1999; Siegel *et al.*, in prep.). The origins of that component, originally identified by Gilmore & Reid (1983), remain a subject of debate, but, since velocity dispersion is a function of age (Wielen, 1977), the thick disk is likely to include the oldest stars in the Galactic disk.

Given the complex kinematics shown by the M-dwarf sample, we do not attempt to model the  $(U, V)$  velocity distribution. Instead, we conduct a simple empirical comparison. Figure 3 plots  $(U, V)$  data for the RHG M-dwarf sample. Twenty systems lie beyond the  $2\sigma$  CB-disk contours, and would be classed as candidate halo stars by Oppenheimer *et al.* If we assume 95% completeness in the RHG sample, this corresponds to a fractional contribution of  $f_{HVD} = 3.7 \pm 0.8\%$ . This fraction exceeds the expected frequency of subdwarfs in the Solar Neighbourhood,  $\sim 0.2\%$ .

Since the stars plotted in Figure 3 are M dwarfs, we can check whether the high-velocity objects have metallicities are consistent with halo membership. Population II stars have  $[Fe/H] < -1$ ; members of a Population III heavy halo should be significantly more metal-poor, with near-primordial abundances. M subdwarfs are recognisable in

<sup>1</sup> With the addition of new astrometric data, mainly from Hipparcos, approximately 7% of the RHG sample fail to meet the initial absolute magnitude-dependent distance limits. Excluding those stars does not affect our conclusions - none of the high-velocity stars are eliminated - so, for internal consistency, our analysis is based on the original RHG dataset.

having weaker TiO absorption than solar-abundance disk dwarfs with the same CaH absorption (Gizis, 1997), but all of the outliers in Figure 3 have near-solar CaH/TiO bandstrength ratios (Figure 4). Thus, the high-velocity M dwarfs are members of a disk population, probably the thick disk. It would be surprising if these main-sequence stars were to lack degenerate counterparts, and as the oldest disk stars, the cooling times can be sufficiently long to achieve temperatures of less than 3000K, similar halo white dwarfs.

### 3. WHITE DWARFS, DARK MATTER AND THE THICK DISK

We have argued that the morphological similarities between Figures 1 and 3 indicate that a sizeable fraction of the O2001 white dwarf sample are members of the Galactic disk. Those similarities are emphasised in Figure 5, where we superimpose the two distributions. At least half of the O2001 white dwarfs are aligned in U with the M-dwarf distribution (at 7 o'clock and 11 o'clock, relative to the centre of the disk ellipsoid).

In order to estimate the likely number of high-velocity white dwarfs contributed by the disk, we need to estimate the density of the parent population, comprising not only white dwarfs, but also their main-sequence progenitors. The latter are included in the calculation since  $f_{HVD}$  gives the fraction of high-velocity stars within a particular mass range, summed over all ages. We assume that all stars, regardless of mass, undergo the same statistical dynamical evolution over the history of the Galactic disk. White dwarfs are the older members of the subset of stars with masses in the range  $\sim 1$  to  $8 M_{\odot}$ , just as chromospherically inactive dM dwarfs are the older members of the  $\sim 0.2$  to  $0.5 M_{\odot}$  stars plotted in Figure 2. The main-sequence progenitors need to be included in the intermediate-mass analysis, just as dMe dwarfs are included in the sample plotted in Figure 2. Thus, the expected density of high-velocity disk white dwarfs is given by

$$\rho_{HVD} = f_{HVD} \cdot (\rho_{WD} + \rho_{MS})$$

The simplest method of making this calculation is to use statistics for nearby stars. Twelve white dwarfs within 8 parsecs are currently known: seven single stars, two wide companions of low-mass red dwarfs (40 Eri B and Stein 2051B), two companions of massive stars (Sirius and Procyon) and one unresolved companion of an M-dwarf (G203-47B; see Reid & Hawley, 2000). Excluding the binaries, the local number density is

$$\rho_{WD}(\text{disk}) = (3.26 \pm 1.23) \times 10^{-3} \text{ stars pc}^{-3}$$

where the cited uncertainty reflects only Poisson statistics. In comparison, Liebert *et al.* (1988) derive

$$\rho_{WD}(\text{LDM}) = 3.0 \times 10^{-3} \text{ stars pc}^{-3}$$

from analysis of white dwarfs found in proper motion surveys. A recent study by Mendez & Ruiz (2001), based on a more extensive sample, gives

$$\rho_{WD}(\text{LDM}) = 2.5 \times 10^{-3} \text{ stars pc}^{-3}$$

Both are broadly consistent with the density estimate derived from the nearest stars.

The 8-parsec sample includes ten main-sequence stars (including Sirius and Procyon) with masses exceeding  $1 M_{\odot}$  and main-sequence lifetimes less than 10 Gyrs, giving an effective local number density of

$$\rho_{WD} + \rho_{MS} = (7.9 \pm 1.9) \times 10^{-3} \text{ stars pc}^{-3}$$

Applying the appropriate correction factor of  $f_{HVD} = 3.7\%$ , we have

$$\rho_{HVD}(\text{disk}) = (2.9 \pm 0.7) \times 10^{-4} \text{ stars pc}^{-3}$$

Again, the uncertainty reflects counting statistics. White dwarfs in the stellar halo are also expected in the Solar Neighbourhood. Assuming that the initial mass function,  $\Psi(M)$ , is similar to that of the disk, as suggested by observations of globular clusters (Piotto & Zoccali, 1999), then these stars contribute an additional  $2 \times 10^{-5} \text{ stars pc}^{-3}$  (Gould *et al.*, 1998). Thus, based on the properties of the known stellar populations in the Solar Neighbourhood, we expect a total density of high-velocity white dwarfs of

$$\rho_{WD}(\text{HV}) \approx (3.1 \pm 0.7) \times 10^{-4} \text{ stars pc}^{-3}$$

This is entirely consistent with  $\rho_{WD}(\text{HH})$ , the space density of high-velocity white dwarfs derived by Oppenheimer *et al.* for their sample of 38 cool white dwarfs.

These calculations can be taken a step further. While the majority of the white dwarfs in Figure 1 can be accommodated in the Galactic disk, a minority have substantial heliocentric velocities and are more likely to originate in a pressure-supported halo population. In a non-rotating system we expect equal numbers of prograde and retrograde rotators, so we can use the number of retrograde-rotating white dwarfs to estimate the local density of that population. We measure  $V < -220 \text{ kms}^{-1}$  for four white dwarfs: F351-50, LHS 147, WD0135-039 and WD0300-044. All four are brighter than the  $R59F=19.7$  completeness limit cited by Oppenheimer *et al.* for their survey. Summing  $\frac{1}{\sqrt{m_{ax}}}$ , allowing for 10% sky coverage, gives a density of  $\rho = 0.91 \times 10^{-5} \text{ stars pc}^{-1}$ . Doubling that value to take prograde rotators into account gives

$$\rho_{WD}(\text{halo}) = 1.8 \times 10^{-5} \text{ stars pc}^{-3}$$

If we adopt the O2001 prescription for deriving (U, V), four additional white dwarfs have retrograde motion: WD0153-014, LHS 542, WD0351-564 and LP586-51. Including the contribution of the three stars which satisfy the completeness limit (WD0351-564 has  $R59F=19.72$ ) increases the derived density by less than 40% giving

$$\rho_{WD}(\text{halo}) = 2.4 \times 10^{-5} \text{ stars pc}^{-3}$$

Either value is consistent with that expected for white dwarfs in the Population II halo (Gould *et al.*, 1998).

In summary, high-velocity disk stars can account for  $\sim 75\%$  of the white dwarfs discovered by Oppenheimer *et al.* (2001). The remaining stars, particularly the retrograde rotators, are explained as members of the classical halo. Given these results, we do not believe it necessary to invoke any contribution from hypothetical white dwarf members of a dark-matter, heavy halo.

Despite our disagreement over the interpretation of these results, it is clear that the stars discovered in Oppenheimer *et al.*'s South Galactic Cap survey represent a significant addition to the catalogue of cool white dwarfs. Besides providing further insight on cooling processes during the final stages of evolution of degenerate dwarfs, statistical analysis of the sample can provide important information on the star formation history of the Galaxy. In particular, if we are correct in our conjecture that the bulk

of these stars are members of the thick disk, then their luminosity function can be used to probe the age of that sub-population, calibrating the first epoch of star formation within the Galactic disk.

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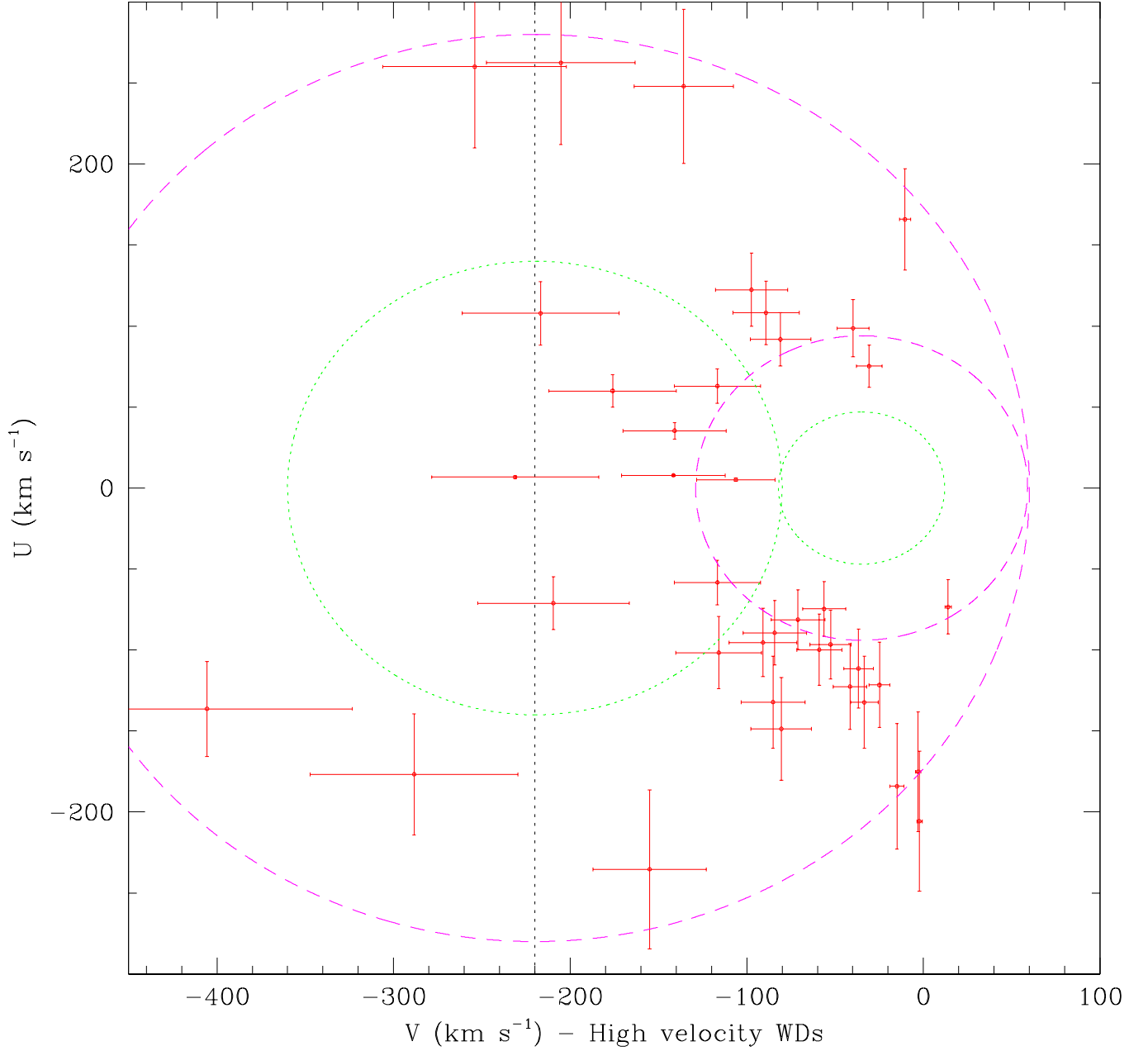


FIG. 1.— The  $(U, V)$  velocity distribution for the 38 candidate halo white dwarfs from Oppenheimer *et al.*. The velocity zeropoint in  $V$  is defined by the Local Standard of Rest; the vertical dotted line marks  $V = -220 \text{ km s}^{-1}$ , corresponding to zero net rotation. The ellipsoids plot the  $1\sigma$  (dotted) and  $2\sigma$  (dashed) contours for the Galactic disk and stellar halo populations, based on kinematics from Chiba & Beers (2000). The errorbars reflect distance uncertainties of 20%, and are therefore correlated in  $U$  and  $V$ . Other possible systematics are not taken into account.

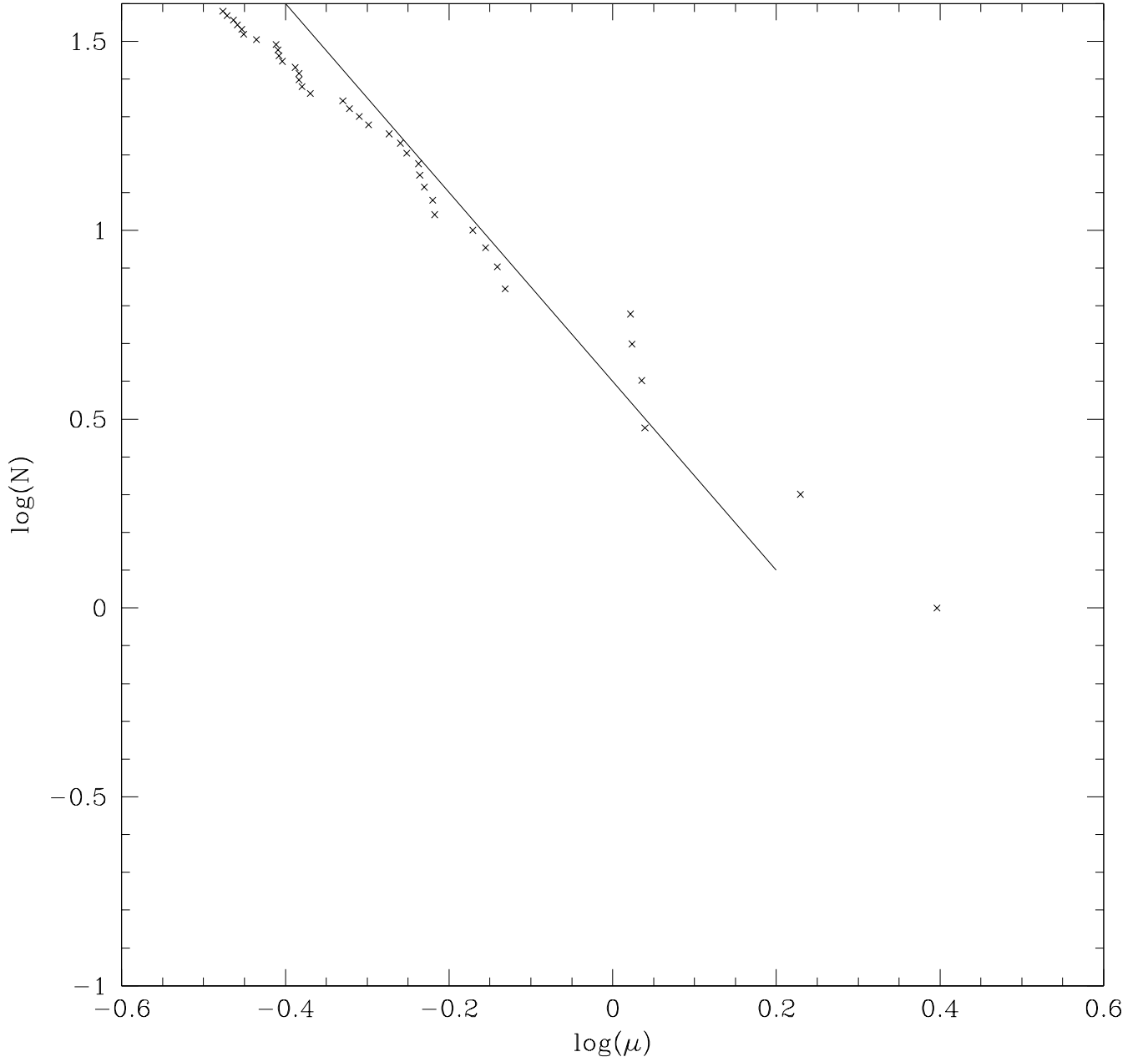


FIG. 2.— The cumulative distribution of proper motions for the O2001 white dwarfs. The solid line plots  $N \propto \mu^{-2.5}$ , shallower than expected for a volume limited sample. The comparison suggests only minor incompleteness at high  $\mu$ , even at motions exceeding 1 arcsec  $\text{yr}^{-1}$ .



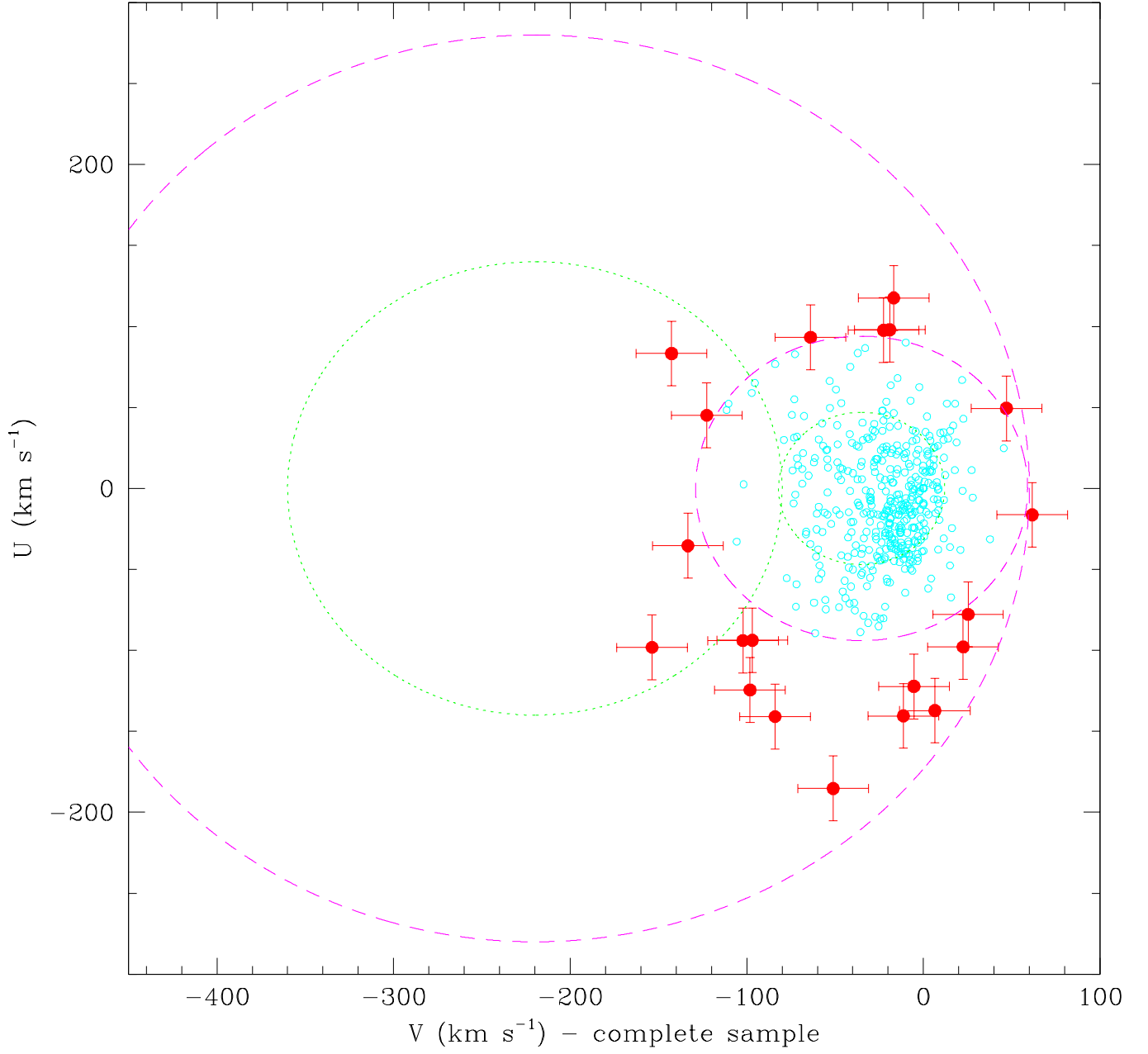


FIG. 3.— The  $(U, V)$  velocity distribution for a volume-complete sample M-dwarf systems (from Reid, Hawley & Gizis, 1995). All of the stars are members of the Galactic disk; 20 stars, identified as solid points with  $\pm 20 \text{ km s}^{-1}$  errorbars, lie outside the  $2\sigma$  disk velocity contours.

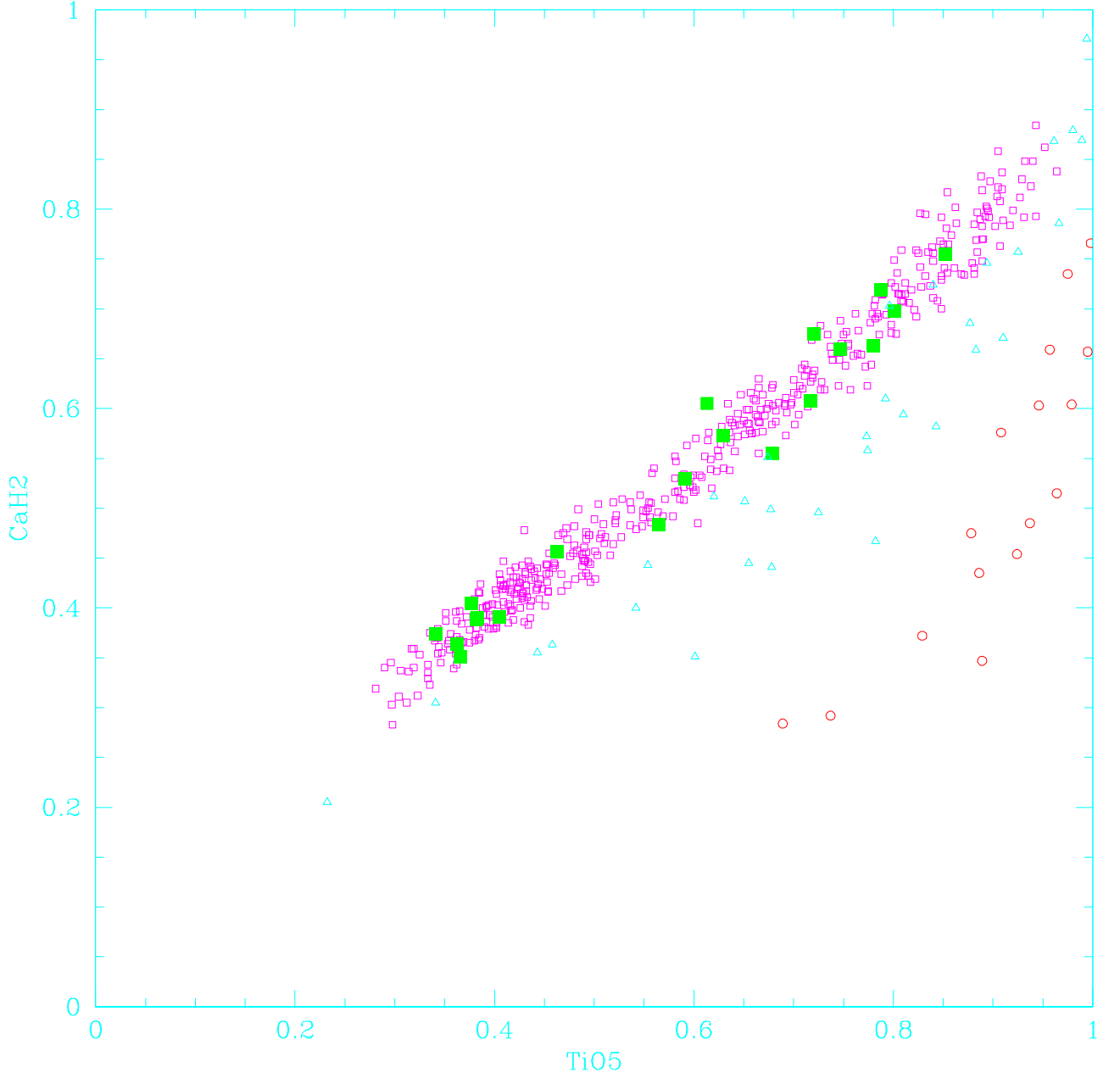


FIG. 4.— The (TiO5, CaH2) diagram for late-type dwarfs: both TiO5 and CaH2 decrease in value with decreasing temperature, and the sequence runs from  $\sim$ K7 to  $\sim$ M8. Data for the complete sample of nearby dwarfs are shown as open squares, with solid squares denoting the 20 high-velocity dwarfs. Metal-poor stars fall below the disk sequence: intermediate-abundance halo subdwarfs ( $[\text{Fe}/\text{H}] \approx -1$ ) are plotted as open triangles, while extreme metal-poor subdwarfs ( $[\text{Fe}/\text{H}] \approx -2$ ) are plotted as open circles (from Gizis, 1997). It is clear that the high-velocity dwarfs have near-solar abundance.

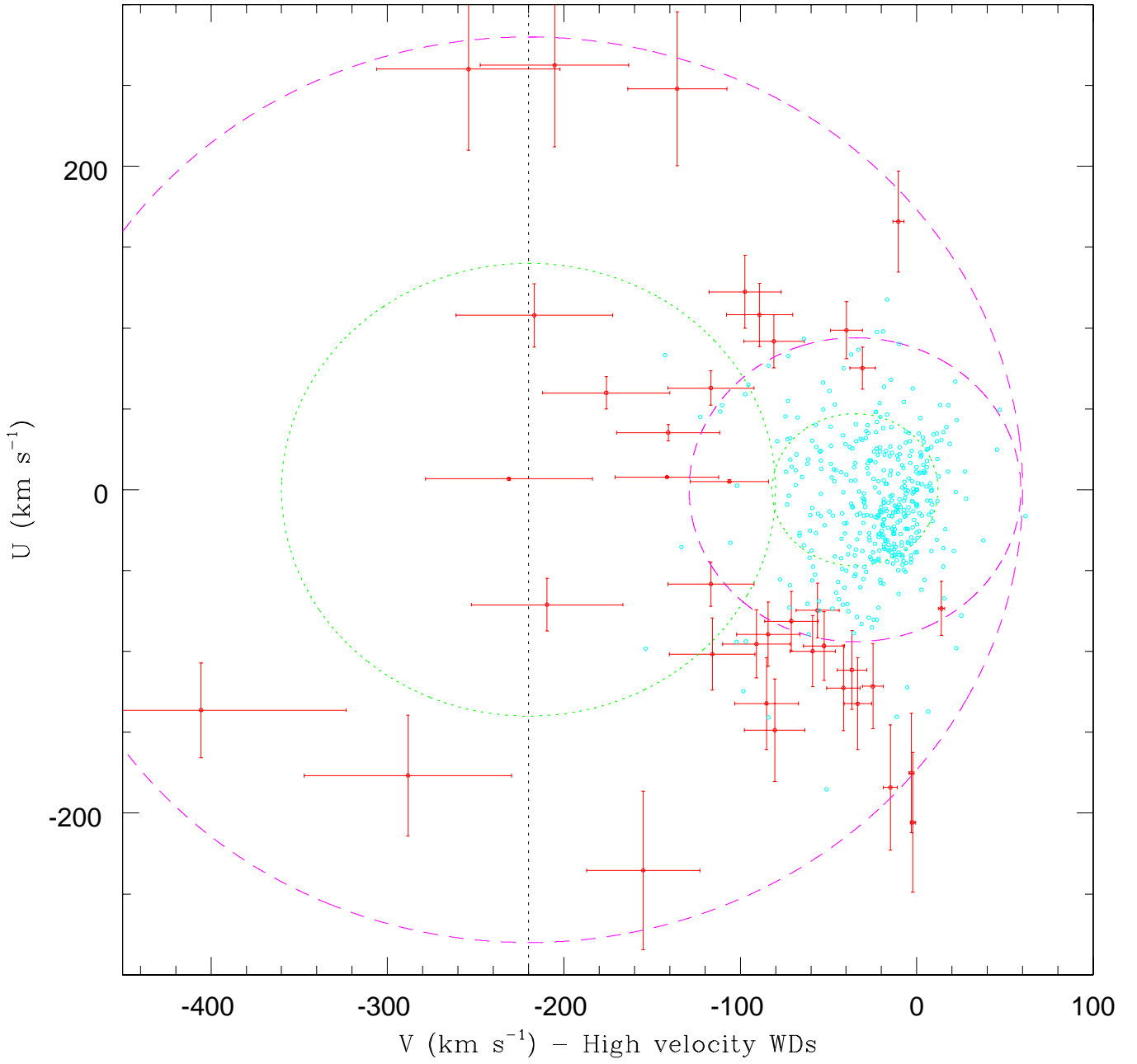


FIG. 5.— The combined  $(U, V)$  velocity distribution of nearby M dwarfs (plotted as open circles) and O2001 white dwarfs (points with error bars). Note the concentration of the latter stars towards the  $U$ -velocity extremes of the M-dwarf distribution. The contours have the same meaning as in Figures 1 and 3.